- Size of each run
- Parameters for each run

In addition to BER measurements, the block[4] error rate was also recorded, since it may be a more meaningful indicator of audio performance.

DAB INTERFERENCE TO FM SIGNAL MODELING

In addition to the model which simulates the DAB receiver, transmitter, channel, and receiver chain, an SPW model to test the performance of the host analog FM in the presence of the DAB sidebands and first-adjacent hybrid FM/DAB signal was developed. The principal block diagram of the simulation model is shown in Figure 4. It was constructed to allow maximum flexibility in analyzing the impact of DAB, with regard to DAB power level and spectral position.

The primary purpose of this simulation model was to assess the impact of:

- DAB interference to the host FM signal, and
- First-adjacent DAB interference to the desired FM signal.

After extensive analysis and simulations, it was concluded that the host DAB is optimally placed 129 kHz away from the FM carrier, on both sides, to minimize the impact to the host FM signal. Such positioning of the DAB signal will result in interference with the first-adjacent FM signal; however, in most of the protected coverage area, the first-adjacent FM signal will have considerably lower power level than the desired DAB signal. Normally, the post-detection noise floor will be measured to investigate the impact of DAB

---

3 Cd/No is the total DAB power to noise power spectral density and is given in dB-Hz.
4 A block is a group of bits whose size corresponds to a syllabic interval.

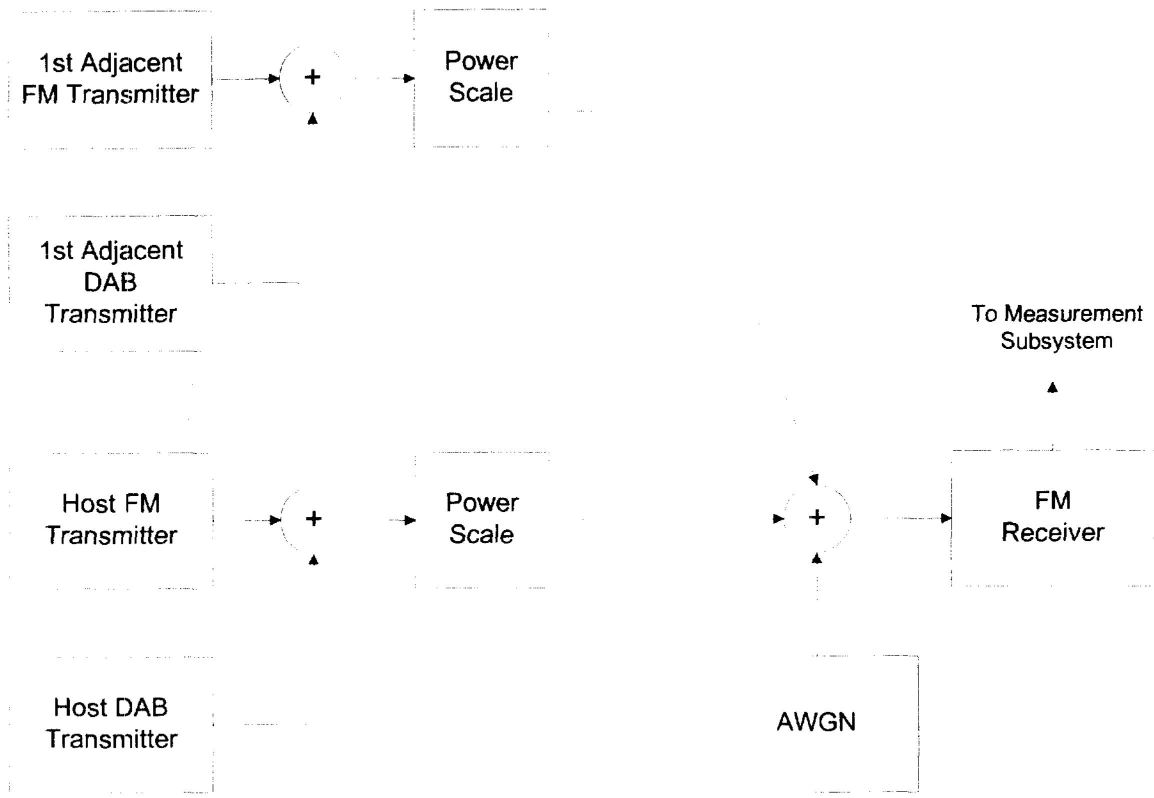

Figure 4. Simulation model to test performance of host FM in the presence of host DAB and first-adjacent IBOC FM/DAB.

SIMULATION RESULTS

<u>DAB Performance</u>

The model of the IBOC FM/DAB system was simulated extensively under extremely adverse conditions and assumptions. After verifying the correct operation of all modules, and the overall system, systematic simulations for different operational scenarios were performed. Figures 5 and 6 summarize simulation results for the 9-tap Urban Fast Rayleigh multipath model specified in Table 1.

Figure 5 shows the hybrid system block error rate curves versus Cd/No for different levels of first-adjacent channel interference. The virtual CD-quality limits in the protected coverage area are indicated by the bold horizontal lines and the dashed vertical line. The curves can be compared with the interference-free case, for the same channel. As a reference, the block error rates for an AWGN-only channel are also shown. It should be noted that Cd represents the total average received power in the digital portion of the hybrid signal. The channel gain is scaled to unity. For actual, nonscaled, EIA test channel models the resulting performance will be better. It can be seen that the DAB receiver operates robustly in the presence of strong, first-adjacent interfering FM signals. This is primarily due to the efficient functioning of the FAC, but also due to overall robust system design, such as optimum placement of the DAB signal and powerful FEC. Moreover, it can be seen that the receiver is relatively insensitive to variations in the power level of interfering signals, except for extremely large powers of interference (such as +12 dB first-adjacent interference). In this case, the FAC cannot completely eliminate the interference. As a result, the residual FM interference is significant enough to degrade the DAB signal somewhat. Figure 5 indicates that target DAB performance is achieved, even for levels of first-adjacent FM interference exceeding those that will be experienced at the FCC-protected contour.

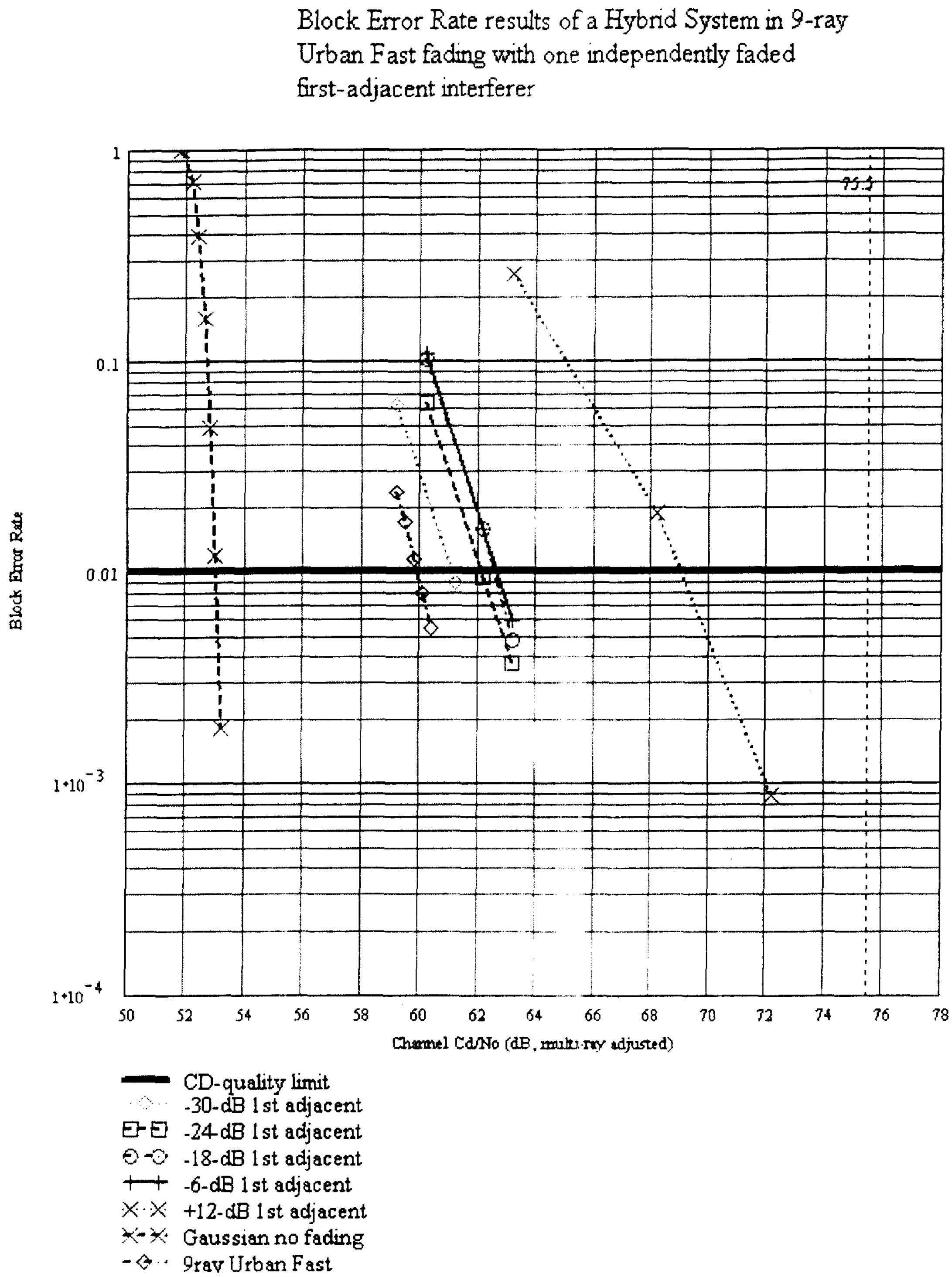

Figure 5. Block error rate versus Cd/No simulation results, with single first-adjacent channel interference.

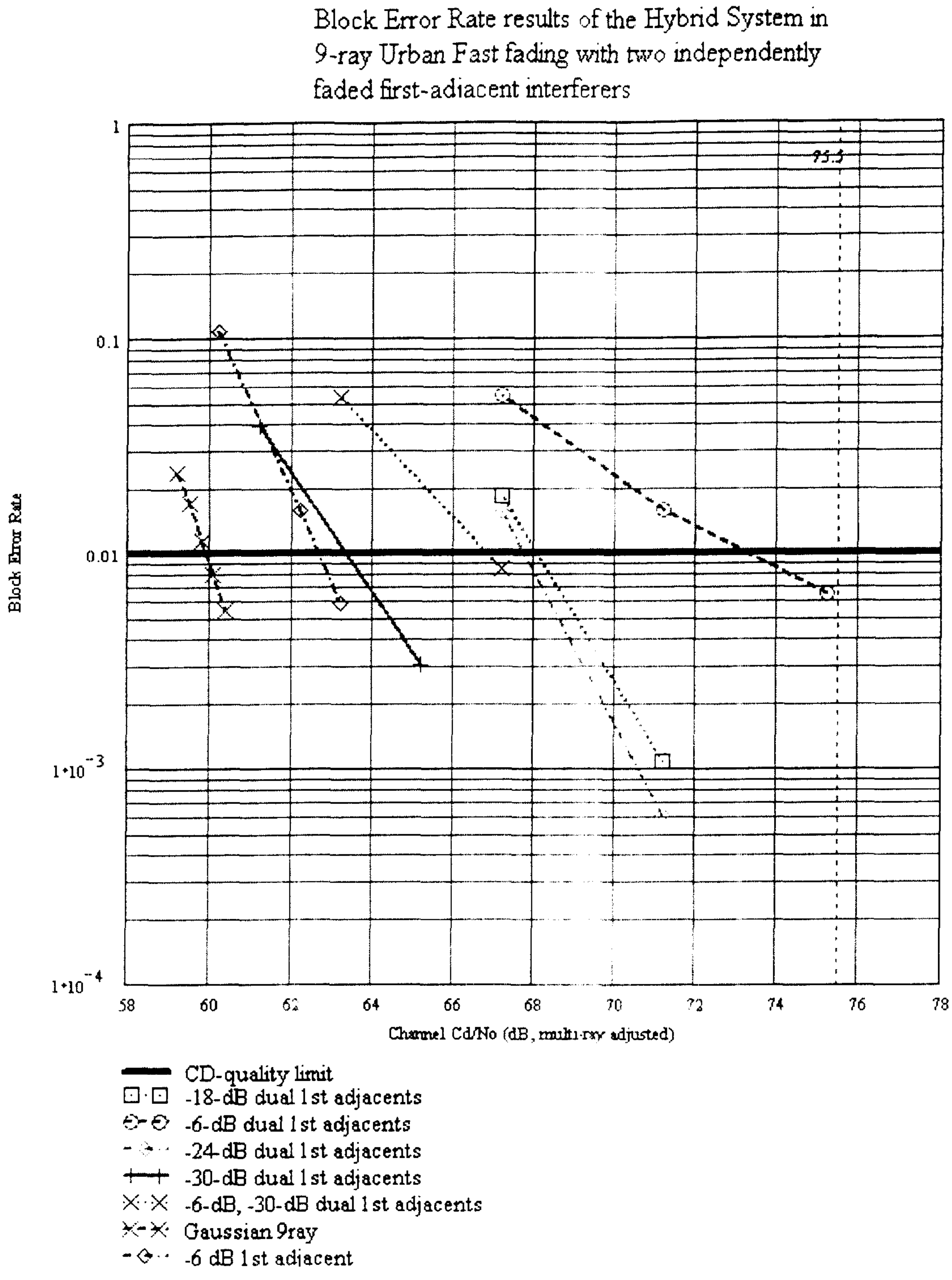

Figure 6. Block error rate versus Cd/No simulation results, with dual first-adjacent channel interference.

Block error rate versus Cd/No curves for several dual first-adjacent interference scenarios is shown in Figure 6. Both DAB sidebands are corrupted by first-adjacent interference. Again, efficient DAB operation with FAC is evident. Although there is some loss (from zero to several dB) in performance when both sidebands are corrupted, the system is still able to provide virtual-CD quality in extremely challenging operational conditions. It should be noted, however, that the dual -6 dB first-adjacent interference case in Figure 6 corresponds to a small fraction of operational situations which are highly geographically localized.

In addition to robustness in the presence of interference, these results clearly demonstrate that receivers successfully operate under practical impairments, such that occur in fast, frequency-selective multipath channels.

FM Performance

The impact of DAB on FM signal reception is analyzed by measuring post-detection noise-plus-interference power spectral density (PSD), using the simulation model setup in Figure 4. The results of extensive analysis and simulation of FM performance are presented in Appendix E. Here we will present a sample of representative results that confirm the validity of the simulation model and indicate the results that could be expected in operation.

It was verified by analysis and simulation that the optimum placement of the DAB signal is 129 kHz away from the host FM carrier. This accounts for direct DAB power impact as well as intermodulation products due to the presence of DAB signal and nonlinear FM detection phenomena. It was also observed that noise-plus-interference level increases by increasing the

FM deviation. However, this effect will not have noticeable impact on audio quality because of a self-masking effect. That is, the noise is smaller when the signal is weaker and highest only when the audio is loudest. In conclusion, based on results of simulations, we expect the presence of a DAB signal will have a minimal impact on audio quality of the host FM signal.

The impact of DAB on an adjacent FM signal at the FCC-protected contour is assessed because, in this case, the DAB will cause interference to a first-adjacent FM channel. Figure 7 shows the impact of a first-adjacent DAB on FM post-detection noise-plus-interference PSD. Specifically, the noise PSD at the FCC-protected contour is compared with and without a first-adjacent IBOC FM/DAB signal. It can be seen that the first-adjacent DAB signal causes an increase in the noise floor. However, the SNR is still an acceptable 50 dB In real receivers, the noise floor is higher than in the simulated receiver, and this effect may not be significant. Although this will result in a slight degradation in the audio quality (in the case of mono reception it will be even smaller), the effect is highly geographically localized near the FCC-protected contour and will rapidly decay as the receiver gets closer to the desired transmitter. Moreover, the present system design will enable the use of smaller DAB transmit power levels, resulting in a corresponding reduction in interference to the FM reception.

These results, as well as more detailed analysis, indicate that the presence of DAB in the composite IBOC FM/DAB signal will have minimal impact on FM quality, even at points closest to the first adjacent transmitter, near the FCC-protected contour. Thus, while the penalty is minimal, the benefit of this approach is significant in that it does not require additional frequency allocation and provides a smooth transition to a fully digital system.

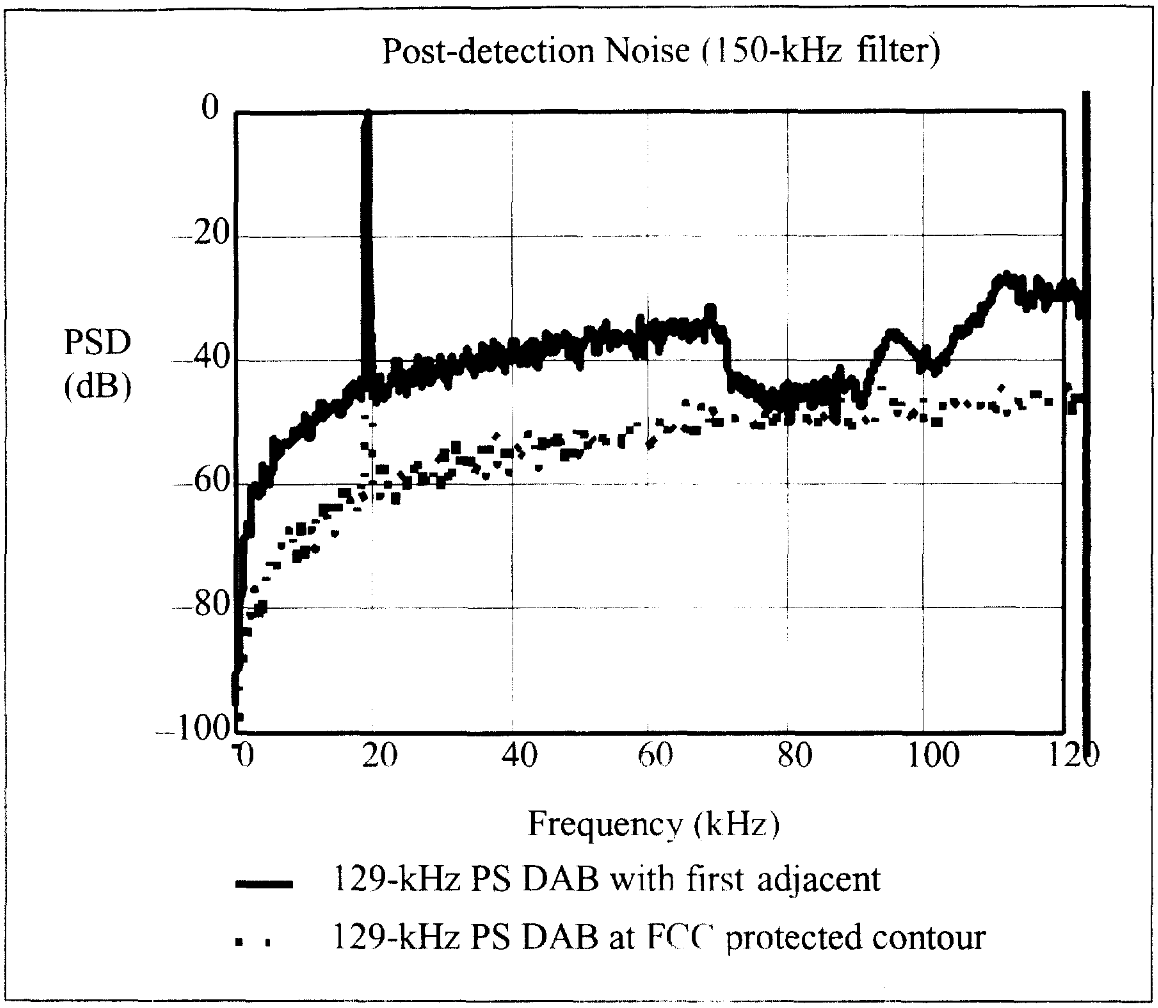

Figure 7. Effect of first-adjacent DAB on FM noise floor, at the FCC-protected contour.

SUMMARY AND CONCLUSIONS OF THE FM IBOC SYSTEM

This report verifies that the IBOC FM/DAB simulator, implemented in SPW, accurately reflects the proposed IBOC FM/DAB system design. As such, the results obtained by a thorough SPW simulation model provide a realistic estimate of performance of the proposed system. Robust performance is achieved in the presence of all important channel impairments, such as fast, frequency-selective fading and strong interference that could be expected in system operation. It is demonstrated that a high-fidelity DAB can successfully co-exist with analog FM systems, with minimal impact on FM quality.

In addition to verifying the feasibility of the USADR system design and accuracy of corresponding SPW simulations, we independently examined and confirmed critical elements of the system, either analytically or via numerical and simulation studies in MATLAB. This gives us a high degree of confidence in the proposed design and convinces us of the feasibility of the hybrid solution, IBOC FM/DAB. This system will provide a smooth transition to the all-digital system in the future, without the need for extra radio spectrum resources.

MODELING AND PERFORMANCE OF IBOC AM/DAB SYSTEM

R. L. Pickholtz and B. R. Vojcic

INTRODUCTION

The In-Band On-Channel (IBOC) hybrid of analog AM and Digital Audio Broadcasting (DAB), proposed by USADR represents an efficient proposal for adding the DAB service to existing analog AM service. It exploits the existing inefficiencies in the analog AM channel structure. As such, it does not require new frequency allocations to provide digital service with significantly enhanced performance. In addition to the compatibility with existing analog AM systems, the hybrid system will provide a smooth transition to an all-digital system in the future.

This unconventional approach is based on standard digital communications technologies and enables co-existence of analog and digital signals within existing allocations by virtue of careful engineering design. The current technology of digital signal processing (DSP) and of application specific integrated circuits (ASIC) will enable inexpensive deployment of IBOC AM/DAB. The availability of digital broadcasting technology will also enable adding auxiliary data services in the future.

The IBOC hybrid of AM/DAB presents a different set of problems than that of the hybrid FM/DAB. First, there is less bandwidth available. This means that for bandwidth efficiency, several versions were explored. The baseline system we examined was a 20 kHz system. Second, the AM band is at a much lower frequency than the FM VHF band.

The impairments in this band are dominated by co-channel and adjacent channel interference, impulsive noise, frequency selective effects introduced by large grounded conductive structures (GCS) (such as highway overpasses, power and telephone overhead lines, road signs, etc.), and by long distance skywave propagation at night which can cause a large co-channel and adjacent interferer to appear and fade.

The co-existence of analog AM and DAB will result in a minimal impact on analog AM reception from IBOC interference. At the same time, a higher fidelity digital reception is provided, even under adverse channel and interference conditions. Our confidence in the proposed approach is currently rooted in a sound engineering approach, based on classical communication techniques that exploit the inefficiencies of existing AM channel structure, as well as simulation studies of the proposed system, that account for realistic channel and system impairments.[1]

The principal block diagram of the IBOC, hybrid AM and DAB system is shown in Figure 1. To protect proprietary information and improve the clarity of presentation, we show and discuss only the main functional blocks and avoid unnecessary details. Nevertheless, we believe that what we describe is a proper representation of the simulation developed to model the proposed IBOC AM/DAB system.

---

1 At this writing, while all of the significant impairments are implemented in the simulation, several have not yet been exercised.

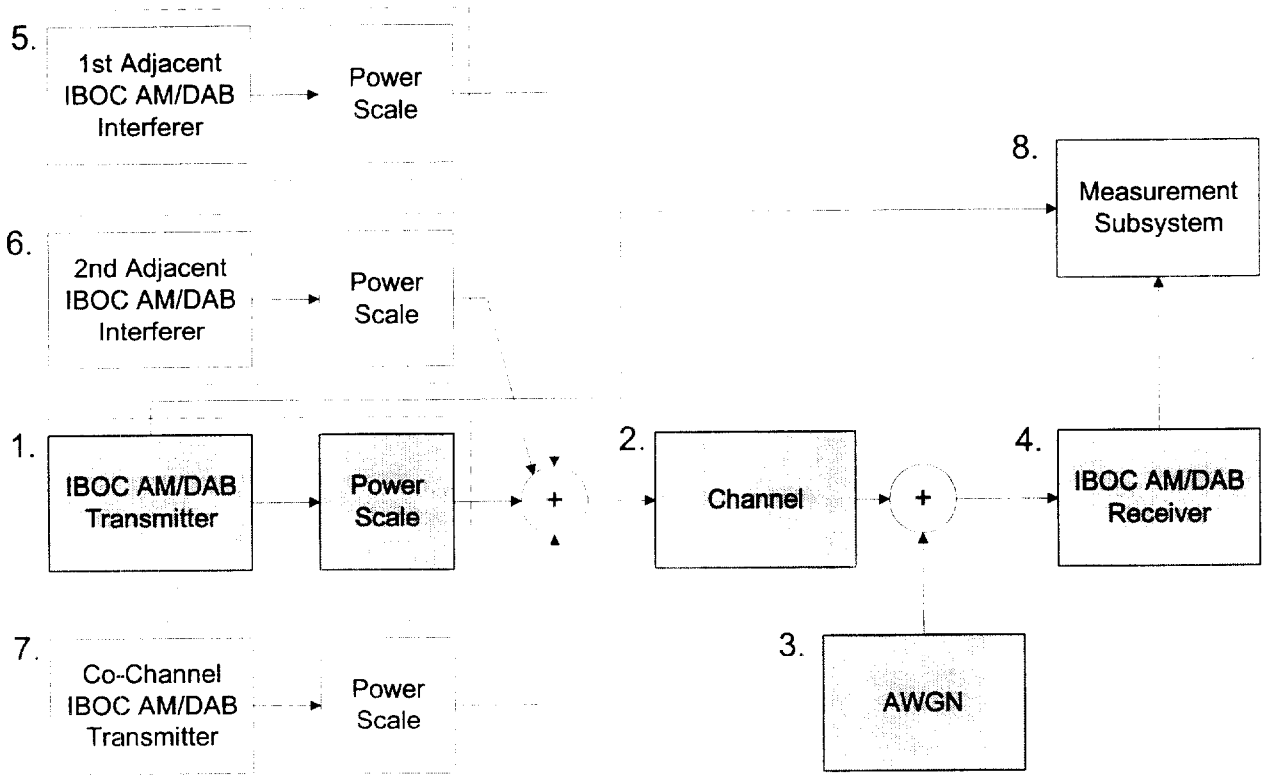

Figure 1. Main block diagram of IBOC AM/DAB system/simulator.

To assess the performance of the proposed system and demonstrate its feasibility, a fairly detailed MATLAB simulator was developed. The MATLAB simulator contains the following main blocks, as shown in Figure 1:

1. IBOC AM/DAB Transmitter
2. Channel
3. Additive White Gaussian Noise (AWGN)
4. IBOC AM/DAB Receiver
5. First Adjacent Channel IBOC AM/DAB Interferer

6. Second Adjacent Channel IBOC AM/DAB Interferer
7. Co-Channel IBOC AM/DAB Transmitter
8. Measurement Subsystem

The first four blocks, 1-4, representing the complete communications chain from source to sink, can be used to analyze the system performance in the absence of interference. However, to obtain a more realistic picture about system behavior, blocks 5-6 are added, enabling analysis of different interference scenarios. The simulator has a built-in capability to employ any combination of blocks 5-7, up to the total of 7 interferers. All transmitted signals, desired and interference, can be independently scaled to provide specified levels of signal-to-noise ratio (SNR) and signal-to-interference ratio (SIR). Blocks 5-7 are identical in structure to block 1, except for a frequency offset, where it is appropriate. Block 8 is used to measure the system performance.

In the subsequent sections, the main blocks of MATLAB-based IBOC AM/DAB simulator will be described in more detail.

TRANSMITTER MODELING

The block diagram of the IBOC AM/DAB transmitter is shown in Figure 2. The Source Generator emulates the audio encoder in simulations. Information bits are forward error correction (FEC) encoded and the coded sequence is interleaved prior to 32-QAM Constellation Mapping. The complex numbers corresponding to 32-QAM symbols are processed in blocks of 256 symbols via Inverse Fast Fourier Transform (IFFT) to generate the OFDM signal.

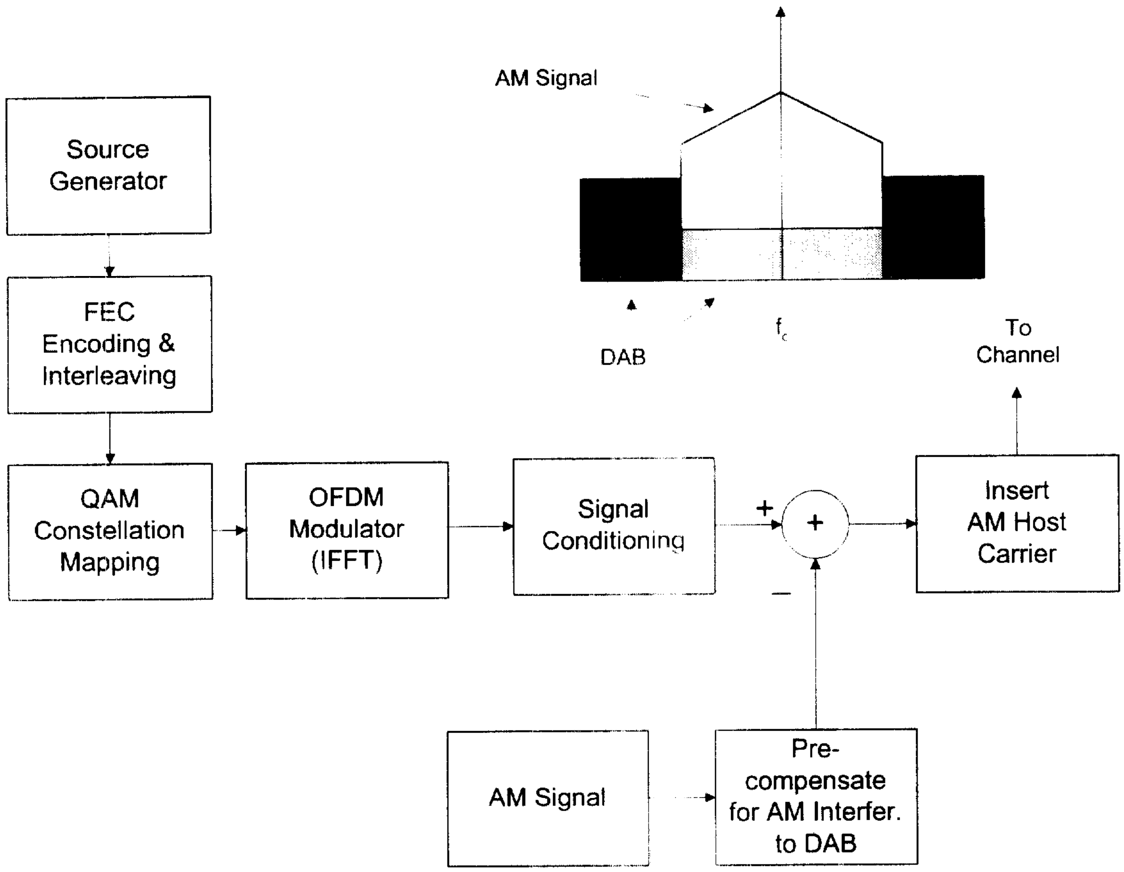

Figure 2. Simplified block diagram of IBOC AM/DAB transmitter.

To maximize the channel utilization, the subcarriers are loaded with QAM symbols in a unique way, shown in Figure 2. Specifically, the subcarriers outside (darkly shaded) the AM signal spectrum are each loaded with one 32-QAM symbol. The remaining carriers that are placed in the AM signal bandwidth (lightly shaded) are placed in Quadrature to the AM signal. The information within the analog spectrum is "free" because it is achieved without interfering with the AM signal under normal circumstances. This is a classical approach known as Quadrature multiplexing. Because USADR has several different modes in the implementation of its IBOC AM system, resulting in slight variations of subcarrier constellations, we avoid describing the specifics of each mode.

To attain the desired signal characteristics, additional signal processing, such as signal shaping, is performed in Signal Conditioning. Due to the non-zero sidelobes of outside subcarriers, there is interference from the AM signal to these subcarriers. A block that pre-compensates for AM interference to DAB minimizes this effect. Finally, after insertion of the AM host signal, the composite IBOC AM/DAB signal is filtered and output to the channel.

CHANNEL MODELING

Channel effects are modeled by blocks 2 and 3, Channel and AWGN, respectively, in Figure 1. The Channel block has the following options:

- Clear channel (only delay and attenuation)
- Frequency-nonselective Rayleigh channel
- Channel with measured impairments
- Channel with modeled impairments

Since severe channel impairments are caused by local terrain obstructions, it is assumed that desired signal and interference experience the same channel impairments. In the case of frequency-nonselective fading only, each interference signal passes through a different fading channel, independently of that of the desired signal.

The AWGN block models the thermal noise in the receiver, and can be used to account for the aggregate of other sources of noise and interference, that are not explicitly modeled.

RECEIVER MODELING

The receiver demodulation chain is shown in Figure 3. After front-end filtering and acquiring synchronization, OFDM demodulation is performed by means of the Fast Fourier Transform (FFT). Equalization (single tap equalizer for each subcarrier) is performed to provide an undistorted equivalent channel response. This is an important receiver function in that it provides symmetry over the band and, thus, maintains the orthogonality between digital carriers and the AM signal. Synchronization, control and mode information are extracted to facilitate detection and framing.

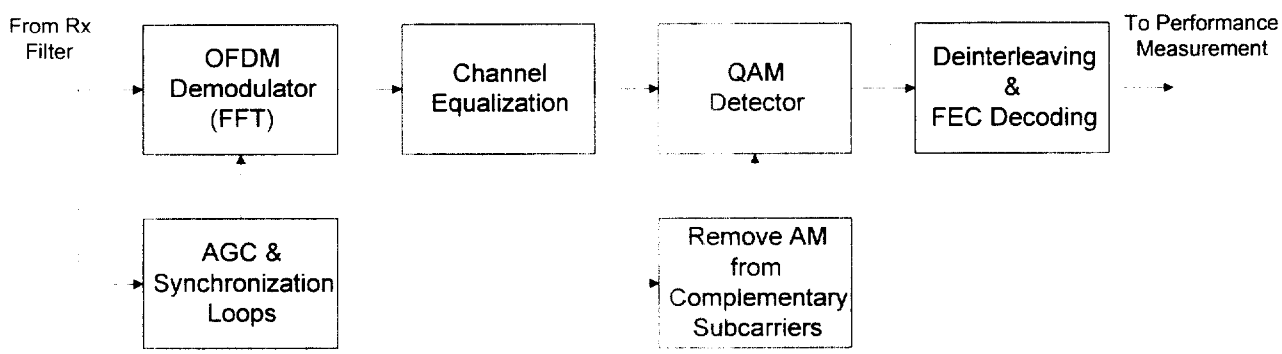

Figure 3. Receiver block diagram.

Equalized subcarriers are processed so that the AM signal is removed from complementary subcarriers by pairing them appropriately. Then all subcarriers are passed to the QAM Detector, where hard decisions are made. A separate sub-block in the

QAM detector observes the QAM constellation points over time to obtain a quality measure ranking for individual symbols. This quality ranking is exploited in the FEC decoding process.

Detected QAM symbols are deinterleaved, to disperse possible burst errors, and fed into FEC decoder. The decoded information blocks are compared with transmitted information blocks in the measurement subsystem

PERFORMANCE MEASUREMENTS

The performance measurement subsystem measures/stores the following:

- Bit/block error rate
- Length of simulation run
- Simulation parameters

Also, probes can be inserted at other places in the block diagram to observe signal distortions or measure signal to noise plus interference ratio (SNIR).

SIMULATION RESULTS

Although the simulator has extensive capabilities, some options are still not fully exercised and/or implemented; a limited number of sample simulations have been performed to prove the feasibility of the proposed concept. Only the hybrid system is considered. However, by design, the all-digital system will have superior performance with comparable interference to analog AM, because its power level will be comparable to that of analog AM.

In this section we first consider the DAB performance in a hybrid signal constellation. Next, the performance of analog AM in the presence of DAB is examined to prove the electromagnetic compatibility of signals in the hybrid system.

DAB PERFORMANCE

The 20 kHz IBOC AM/DAB represents the baseline approach of USADR. The simulations performed indicated that second and third adjacent channel interference are negligible in a 20 kHz system.

The DAB performance is measured in terms of block error rate. The threshold of audibility (TOA) is assumed to correspond to 1% of block errors, which can be concealed by the audio decoder. In the 32 kbps system, which is more robust than the 48 kbps system, the TOA is reached for either co-channel or single first adjacent-channel interference at about –20 dB. The TOA contours when both co-channel and first adjacent-channel interference are present simultaneously are shown in Figure 4, for 32 kbps and 48 kbps codecs, respectively. The thermal noise is ignored because it is not a dominant factor in AM. Naturally, the TOA limit is now closer when compared to a case with a single interferer. For example, the 32 kbps codec can operate below the TOA limit as long as the interferers, of equal power levels, do not exceed –27 dB relative to the signal of interest (SOI). If one of the interferers is at –50 dB, then the other can still be up to –20 dB. Similar TOA contours for two first adjacent-channel interferers, upper and lower, are shown in Figure 5.

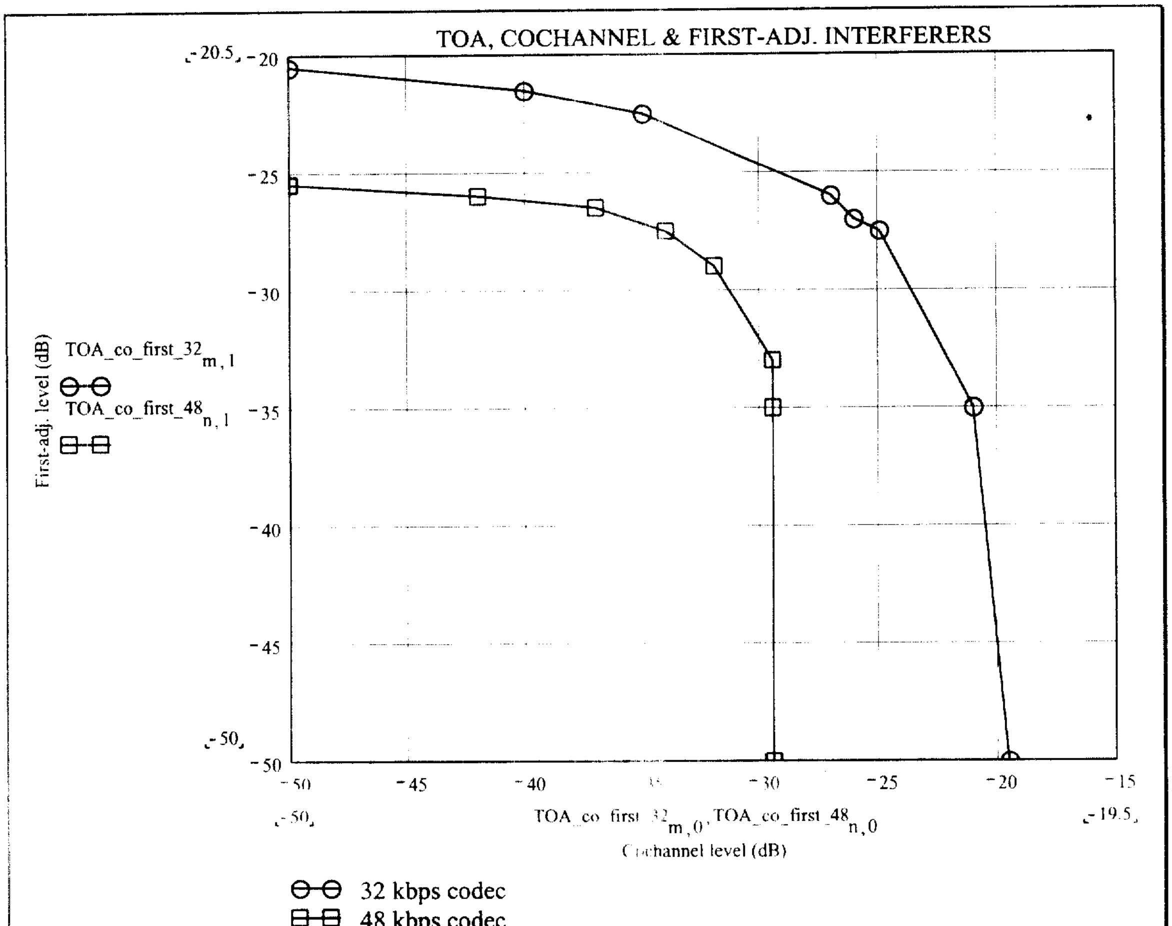

Figure 4. TOA contours for simultaneous co-channel and first adjacent interferers.

These examples demonstrate that the DAB signal reception is successful in the presence of the host AM signal. That is, it is primarily limited by the presence of interferers, as would be the case in current AM systems also

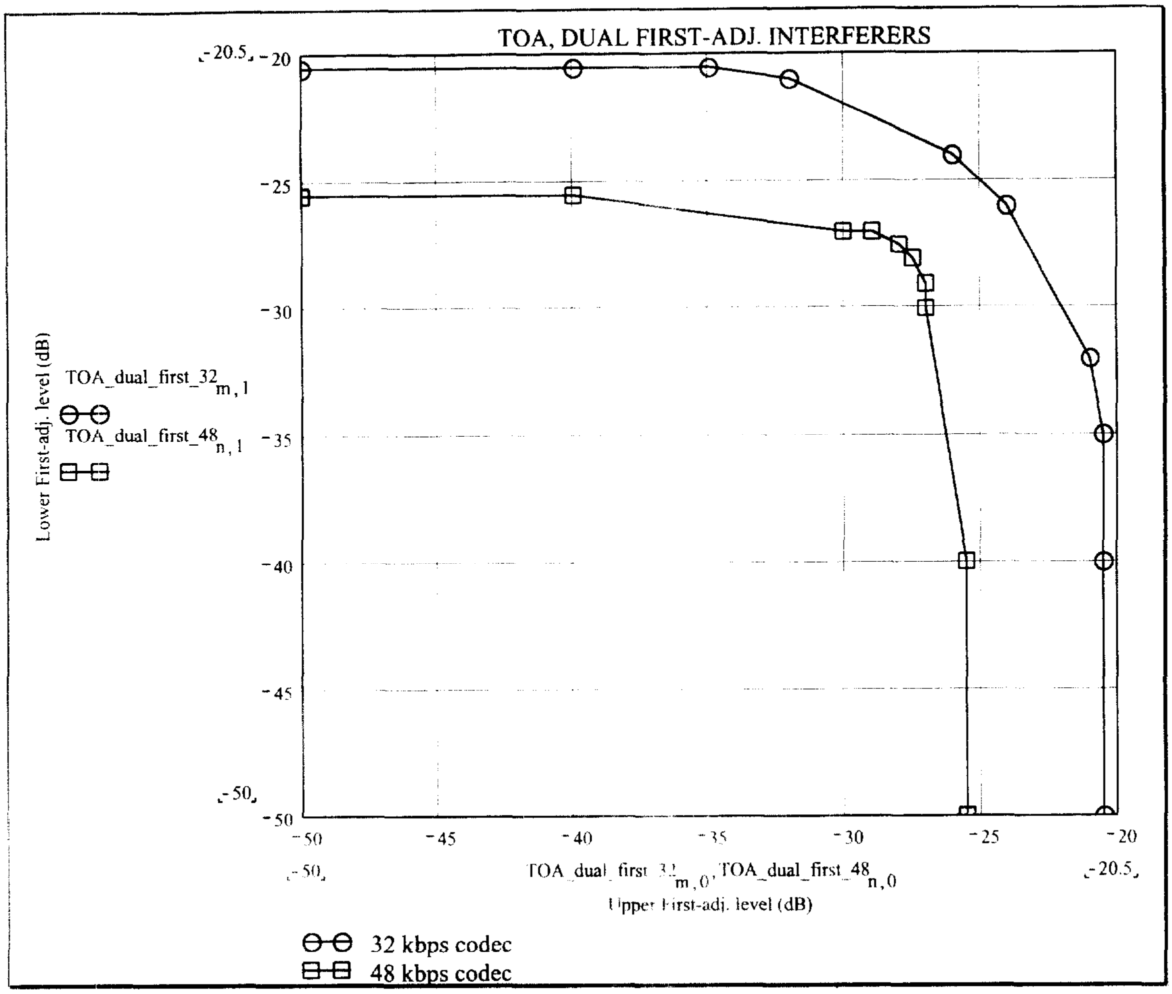

Figure 5. TOA contours for simultaneous co-channel and first-adjacent interferers.

AM PERFORMANCE

In addition to assessing the DAB performance in the hybrid system, it is also important to explore the impact of DAB on analog AM performance, *i.e.*, to verify the compatibility of two subsystems. Since an all-digital DAB can be designed with comparable or lower power levels than the analog AM system, the interference from all-digital DAB to analog AM will be smaller than in an all-analog AM system. Thus, we are primarily interested in the impact of hybrid AM/DAB to analog AM reception. This interference is minimized by the system design, *i.e.*, by the proper placement of DAB subcarriers. The DAB carriers, that are in quadrature to the host AM carrier normally produce a negligible crosstalk to the AM signal, especially in the case of coherent detection. The interference from the analog AM to the DAB will be effected by frequency selective effects, such as those produced by grounded conductive structures. This is accounted for in the receiver design by employing a one-tap equalizer for each subcarrier, to maintain the orthogonality between the AM and DAB signals. Since most existing receivers limit the audio bandwidth to ±5 kHz, the effect of sideband (outside) subcarriers is also minimized.

The proposed hybrid and all-digital IBOC signals will be transmitted with power spectral density comparable to existing AM analog signals. The interference from co-channel or adjacent-channel IBOC interferers will be comparable to the interference from present AM analog signals. Therefore, the IBOC DAB signal is compatible with the existing analog environment. Furthermore, the constant white noise interference of DAB is likely to be less annoying than audio interference at comparable interference power levels. The AM hybrid system employs several techniques to minimize the interference from the digital subcarriers to the analog AM host signal. These techniques include quadrature modulation, setting appropriate power levels, spectral sidelobe reduction, and dynamic pre-distortion. Although this interference in new receivers can be made arbitrarily small, the interference in existing receivers is limited by the non-ideal IF filter asymmetry. Preliminary experiments with automobile receivers with a previous 30 kHz AM DAB signal without the benefit of dynamic predistortion indicate that good SNRs can be obtained with most receivers. However, there are some receivers that are more sensitive to this problem. The present 20 kHz AM DAB signal is designed to reduce this interference even further.

SUMMARY AND CONCLUSIONS

This report verifies that the IBOC AM/DAB simulator, implemented in MATLAB, accurately reflects the proposed IBOC AM/DAB system design. As such, the results obtained by a thorough MATLAB simulation model provide a realistic estimate of the performance of the proposed system. Promising performance is achieved in the presence of all important channel impairments, such as various combinations of co-channel, first and second adjacent channel interference. Additional impairments, such as frequency selective effects of GCS and impulsive noise, are also in the model. The interference was produced by actual AM modulated music and speech. However, the GCS data and the impulsive noise, while present in the model, were not exercised in the current round of simulations for the co- and adjacent channel interference. It is demonstrated that a high fidelity DAB signal can successfully co-exist with analog AM systems, with minimal impact on AM quality.

In addition to verifying the feasibility of USADR system design, and the accuracy of the corresponding MATLAB simulations, we independently examined critical elements of the system and confirmed that the simulator realistically matches the proposed design. This gives us a fairly high degree of confidence that the proposed design of IBOC AM/DAB can successfully operate and offer an improved service quality and a smooth transition to the all-digital system in the future We expect that further investigations, with the inclusion of design refinements, and that also include additional impairments, will continue to uphold this assertion.

VITAE

Raymond L. Pickholtz, professor in and former chairman of the Department of Electrical Engineering and Computer Science at The George Washington University received his Ph.D. in Electrical Engineering from the Polytechnic Institute of Brooklyn in 1966. He was a researcher at RCA Laboratories and at ITT Laboratories. He was on the faculty of the Polytechnic Institute of Brooklyn and of Brooklyn College. He was a visiting professor at the Universite' du Quebec and the University of California. He is a fellow of the Institute of Electrical and Electronic Engineers (IEEE) and of the American Association for the Advancement of Science (AAAS). He was an editor of the *IEEE Transactions on Communications*, and guest editor for special issues on Computer Communications, Military Communications Spread Spectrum Systems and Social Impacts of Technology. He is editor of the Telecommunication Series for Computer Science Press. He has published scores of papers and holds six United States patents.

Dr. Pickholtz is President of Telecommunications Associates, a research and consulting firm specializing in Communication System disciplines. He was elected a member of the Cosmos Club and a fellow of the Washington Academy of Sciences in 1986. In 1984, Dr. Pickholtz received the IEEE centennial medal. In 1987, he was elected as Vice President, and in 1990 and 1991 as President of the IEEE Communications Society. He received the Donald W. McLellan Award in 1994. He was a visiting Erskine Fellow at the University of Canterbury, Christchurch, NZ, 1997.